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INFRARED THERMOMETRY: A REMOTE SENSING TECHNIQUE FOR PREDICTING YIELD IN WATER-STRESSED COTTON

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ABSTRACT

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A crop water stress index (CWSI) was derived from air temperatures, air vapor pressure deficits and the midday radiant leaf temperatures of cotton plants that were exposed to different early-season irrigation treatments at Phoenix, AZ, U.S.A. To calculate the CWSI, an infrared thermometer was used to measure leaf temperatures which were then scaled relative to minimum and maximum temperatures expected for no-stress (CWSI=0) and extreme drought-stress conditions (CWSI=1). Results showed the CWSI behaved as expected, dropping to low levels following an irrigation and increasing gradually as the cotton plants depleted soil moisture reserves. The final yield of seed cotton was significantly inversely correlated with the average CWSI observed over the interval from the appearance of the first square until two weeks following the final irrigation.

INTRODUCTION

In the absence of limiting nutrient deficiencies or pest complexes, water stress is the most important factor influencing normal plant development. As a consequence, a number of methods have been developed to assess its magnitude and establish its relation to growth and harvestable yield. Although some of these methods involve physical measurements of the plants' environment, we believe that the most sensitive and useful indicator of impending water stress should be a physiologically-based plant response. This is because it is the plant itself which is best equipped to integrate an often unknown and complex set of environmental, morphological and physiological parameters which have a bearing on its ultimate water status. A good example of such a plant response is the loss of leaf turgor associated with drought. In fact, the wilting of plant leaves has been used extensively to signal the need for irrigation without any knowledge of the interactions which exist between the water requirements of the plant, the evaporative demand of the atmosphere, root distribution, soil water availability or quality, soil temperature etc. Quantifying a parameter like wilting, however, is difficult if not impossible. Furthermore, it is likely that wilting does not give an early enough warning of stress to permit a grower to alleviate the drought condition before the yield potential is reduced.

On the other hand, many of the conventional and accepted physiologically-based methods for monitoring stress such as leaf water potential, leaf diffusion resistance, relative leaf water content, etc., give quantifiable results that could be used for scheduling irrigations; but these approaches are usually time consuming, error prone and tedious. The required destructive sampling often precludes their repetitive use and probably influences subsequent measurements. Since these methods usually involve point observations, several to many measurements are required to characterize a single experimental treatment, let alone survey an entire field or farm for irrigation scheduling purposes. These disadvantages presently restrict the use of these measurements in studies of plant water relations where numerous treatments must be evaluated within a short period of time. Undoubtedly the same limitations will prevent their widespread acceptance in an applied irrigation scheduling program.

Thus, the agricultural researcher and resource manager alike have an urgent need for a new tool to augment or even replace the more traditional means of quantifying plant stress. Ideally, the approach should provide a rapid, non-destructive, reliable estimate of plant water status which would be amenable to larger scale applications and would circumvent some of the sampling problems associated with point measurements. Several recently developed remote sensing techniques which utilize infrared thermometry to assess plant stress appear to meet these stringent requirements (Jackson, 1982; Pinter, 1982). They have been established as viable methods for monitoring stress and predicting yields in a variety of food and forage crops (Tanner, 1963; Wiegand and Namken, 1966; Idso et al., 1977, 1981a, b; Ehrler et al., 1978; Reginato et al., 1978; Pinter et al., 1979; Walker and Hatfield, 1979; Gardner et al., 1981a, b; Hatfield, 1982). The same infrared techniques are emerging as powerful alternative methods for assessing water potential, diffusion resistance and net photosynthesis of leaves from cotton plants exposed to varying moisture conditions in the field (Idso, 1982a, b; Pinter and Reginato, in press). A logical extension of these findings is to utilize crop canopy temperatures as inputs into the irrigation scheduling decision making process (Jackson et al., 1977; Geiser et al., 1982; Hatfield, in press; Pinter and Reginato, 1982). The purpose of the present report is to document the usefulness of infrared thermometry for predicting lint yield of cotton plants exposed to differing irrigation regimes. This information can be used to develop guidelines for using infrared temperatures for scheduling cotton irrigations, bypassing other more tedious methods for assessing irrigation requirements and directly utilizing an easily measured remotely sensed parameter for this task.

METHODS

Our experiment was conducted in a 2-ha field of upland cotton (*Gossypium hirsutum* L. var. 'Deltapine-70') located on the University of Arizona Cotton Research Center farm in Phoenix, AZ. The soil is an Avondale loam — a fine, loamy, mixed (calcareous) hyperthermic, Anthropic Torrifluvent. Following a preplant irrigation, cotton was planted on 14 April 1980 on east-west oriented rows spaced at 1-m intervals. After emergence, the stand was thinned to a density of approximately 86 000 plants per ha. The experimental design incorporated six replications of six different irrigation regimes wherein the major treatment variable was the date of the first postplant irrigation. Subsequent irrigations were usually given at 2-week intervals. The amount of water applied to each plot was metered through gated pipes and totalled for the entire season. Final yield of seed cotton was determined by machine picking two 12 m long center rows of plants in each treatment.

Radiant leaf temperatures (T_ℓ) were obtained between 13.30 and 13.45 h (Mountain Standard Time) using a handheld infrared thermometer, IRT (approximately 4° field of view, 10.5—12.5-μm bandpass filter) that was calibrated for use in high ambient air temperatures. Average temperatures were obtained by aiming the IRT at eight fully expanded leaves selected at random from the top of the canopy in two replicate plots of each different treatment. Instead of "canopy" temperatures, T_ℓ was chosen because the latter more closely represents temperatures of plant parts, while the former may include a composite of plant and background soil temperatures. No adjustments were made in apparent temperatures for emissivity of the leaves or the radiant flux from the sky. From a practical standpoint, these corrections can be ignored when the primary concern is the relative differences which exist between treatments (Perrier, 1971). Wet- and dry-bulb temperature measurements were made at the start and finish of each set of measurements using an aspirated psychrometer held about 1.5 m above the soil. These data were used to calculate vapor pressure deficits using standard psychrometric relations.

RESULTS AND DISCUSSION

Table I summarizes the irrigation history and yield parameters for the twelve experimental cotton plots. The total amount of applied water ranged from 72 to 113% of the estimated seasonal consumptive water use of cotton in the Phoenix area (Erie et al., 1965). Delaying the first post-plant irrigation past late May represented a deviation from the traditional irrigation practice in this area. In the extreme cases represented by plots E1 and E2, this appeared to impact yield adversely, reducing marketable lint by approximately 500 kg/ha. Furthermore, an interval longer than 2 weeks between successive irrigations tended to lower yield as well. This observation was consistent with the findings of Guinn et al. (1981) where suboptimal moisture during

TABLE I

Irrigation, CWSI and yield parameters for 'Deltapine-70' cotton grown at Phoenix, AZ, in 1980

Plot	# Post-plant irrigations	Total amount[a] of water (cm)	Date of irrigation[d] 24 May	04 June	11 June	17 June	24 June	30 June	08 July	15 July	29 July	12 August	Average[b] CWSI	Seed Cotton (kg/ha)	Lint yield[c] (bales/acre)
A1	7	117.8	X		X		X		X	X	X	X	0.161	3599	2.23
A2	7	115.7	X		X		X		X	X	X	X	0.132	3623	2.24
B1	6	99.6		X		X		X		X	X	X	0.146	4141	2.56
B2	7	114.9	X	X		X		X		X	X	X	0.121	4124	2.55
C1	6	100.8			X		X		X	X	X	X	0.214	3041	1.88
C2	6	99.0			X		X		X	X	X	X	0.201	4012	2.48
D1	5	86.1				X		X		X	X	X	0.215	3179	1.97
D2	6	101.3	X			X		X		X	X	X	0.215	3445	2.13
E1	4	75.1					X			X	X	X	0.269	2685	1.66
E2	4	75.1					X			X	X	X	0.303	2370	1.47
F1	5	88.8	X						X	X	X	X	0.335	1884	1.17
F2	5	90.9	X						X	X	X	X	0.194	3332	2.06

[a]This amount also includes approximately 27 cm of water from winter rains and a single preplant irrigation.
[b]Calculated as the mean CWSI observed over the interval from the appearance of the first square (31 May) until 2 weeks following the last irrigation (27 August)
[c]Based on the approximations that lint yield is 33.3% of seed cotton and one bale of lint weighs 217.4 kg.
[d]Plots with the same letter designators were originally intended to be treatment replicates. Breaks in the berms that separated adjacent plots resulted in Plots B2 and D2 receiving an unintended irrigation on 24 May.

blooming reduced final yield by decreasing the number of sites available for cotton formation. We found, however, that the amount and timing of water applications did not explain the unusually high variability observed between plots which would, in the traditional agronomic sense be considered as treatment replicates (i.e., plots F1 and F2). To explain this apparent paradox, the next step in our analysis required that we observe the plants themselves for a season-long estimate of yield reducing stress.

The crop water stress index (CWSI) provides a relative measure of plant stress which is derived from radiant leaf temperatures and ambient meteorological parameters. In order to calculate the CWSI, observed leaf temperatures are scaled relative to the minimum and maximum leaf temperatures that would be expected under no stress (CWSI=0) and extreme stress conditions (CWSI=1), respectively. These boundary conditions can be specified in two ways: (1) theoretically, from energy balance considerations (Jackson et al., 1981); or (2) empirically, using observations from plants in the field which are known to be transpiring at near maximum and minimum rates (Idso et al., 1981c, Idso, 1982). Both methods acknowledge that the difference in temperature between the leaves and air is a function of the evaporative demand of the atmosphere—predominantly vapor pressure deficit

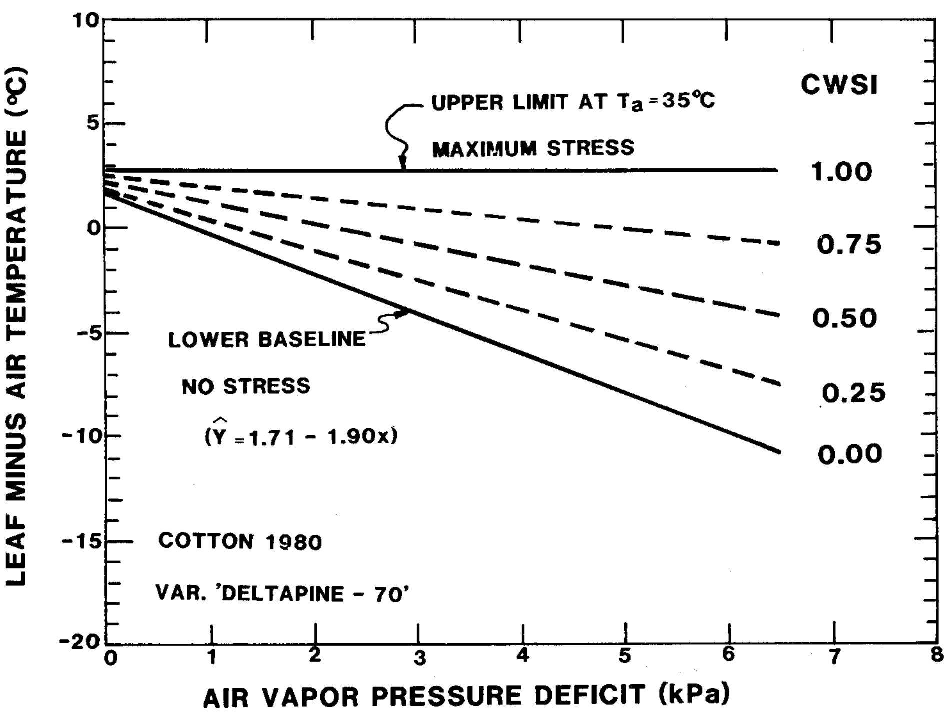


Fig. 1. A diagrammatic representation of the algorithm relating the difference between leaf and air temperatures over a range of atmospheric vapor pressure deficits and plant stress conditions.

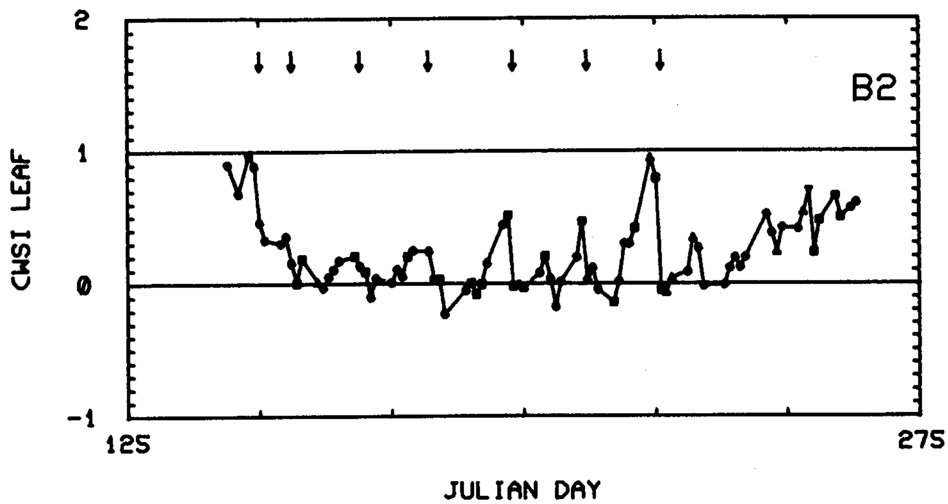
(VPD), but the Jackson et al. (1981) method also requires a measurement of net radiation. The CWSI values used in this analysis were based on the methods outlined by Idso et al. (1981c). We observed, for example, that T_ℓ of well-watered cotton was about 4 °C below T_a at VPD=3.0 kPa, and almost 9°C below T_a when the air VPD had increased to 5.5 kPa. Similar data for well-watered cotton throughout the season were used to generate the no-stress baseline temperatures for cotton (Pinter and Reginato, 1982):

$$T_\ell - T_a = 1.71 - 1.90\,(\mathrm{VPD}) \qquad R = 0.67 \quad n = 133 \tag{1}$$

where $T_\ell - T_a$ is in °C and VPD is in kPa. The upper limit representing $T_\ell - T_a$ for plants which are severely stressed was shown to be relatively constant at about +3°C. The CWSI is defined within the range over which T_ℓ can vary due to water stress conditions. The CWSI is the ratio of the deviation of the measured $T_\ell - T_a$ from the well-watered baseline to the complete range of temperatures possible at a given VPD. The CWSI is dimensionless and theoretically varies from near zero for non-stressed plants transpiring at potential rates to unity for severely stressed plants which are not transpiring. Diagrammatically, the CWSI concept for cotton is shown in Fig. 1. The area which is bounded by the upper and lower baselines encompasses possible values of observed $T_\ell - T_a$; their location in the data space, of course, is dependent on plant moisture stress and VPD. The dashed lines indicate various intermediate levels of CWSI. Since the dynamic range of possible leaf temperatures increases with increasing VPD, the CWSI is most sensitive to plant water stress under conditions of maximum evaporative demand (i.e., high ambient air temperatures and/or low vapor pressures).

When calculated values of the CWSI were graphed against time for each cotton plot, we observed patterns which were synchronous with irrigation events. Fig. 2 illustrates this relationship using data from both the highest (B2) and lowest (F1) yielding plots. Early in the season the plants were small and their leaf temperatures were closely coupled to the hot soil thermal regime. Thus, the CWSI values were relatively high, remaining well above zero even immediately following irrigation when we considered their water status to be near optimum. By mid-June (day 160) however, the plants were approximately 30 cm in height and 20—25 cm in width, and had begun to modify their microclimate. Well-watered plants at this stage of growth exhibited leaf temperatures which fell on the baseline described by Equation 1. As a consequence, the CWSI generally dropped to zero or lower following each irrigation, but then increased steadily to a maximum value just prior to the next irrigation.

Major differences between irrigation treatments and replicates became evident when daily CWSI values were summed throughout the season (Figs. 3A and 3B). We observed an inverse relation between the amount of water added and the running accumulation of CWSI. This is illustrated in Fig. 3A, where a two-fold increase in yield occurred when the amount of water ap-



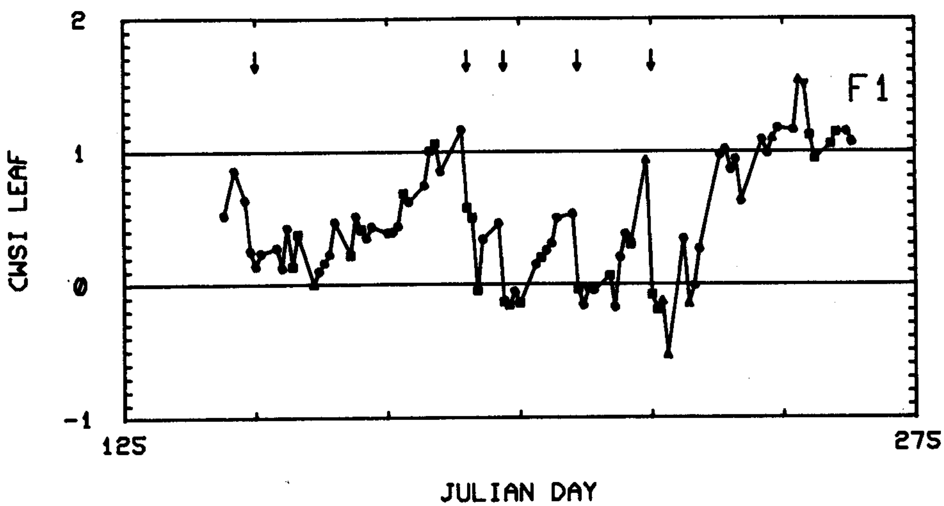


Fig. 2. The seasonal trend of the daily CWSI for two different irrigation treatments wherein yield differences were at maximum. Arrows along the upper axis represent irrigation events.

plied was doubled. Dramatic differences between "replicates" of the same irrigation treatment (plots F1 and F2) were quite evident in the accumulated CWSI data shown in Fig. 3B. Since these differences also appeared to explain the unusual variability in yield which we observed between these plots, we felt that the CWSI might offer a powerful tool for inferring stress and monitoring yield potential.

Accordingly, an 88-day interval was selected as representing the period of

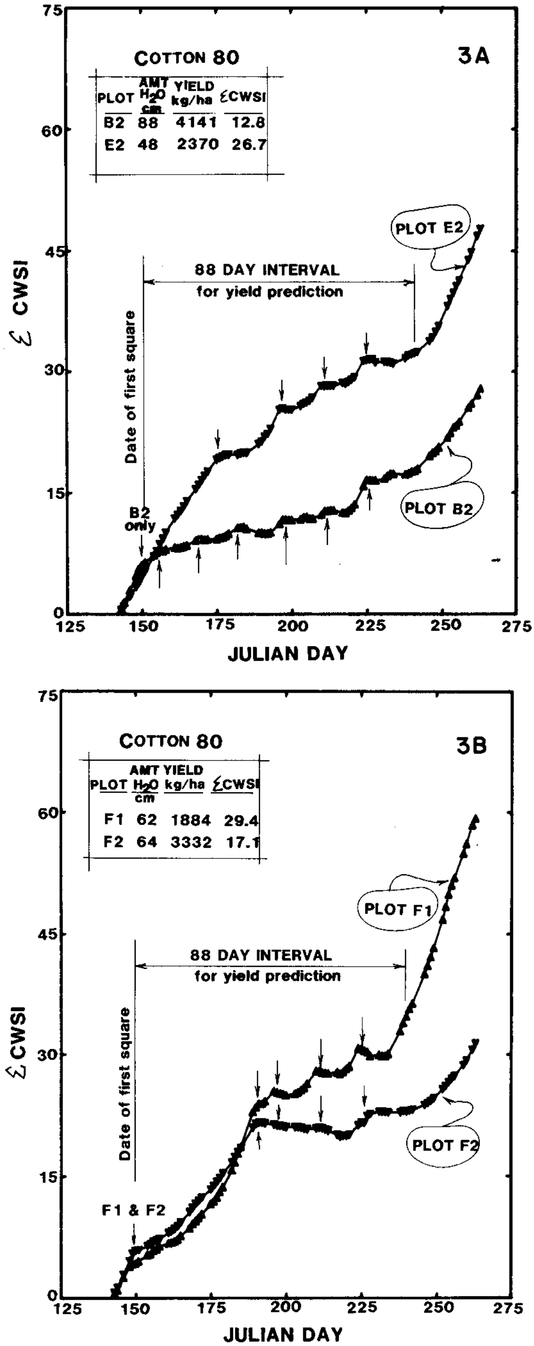


Fig. 3. Season-long running accumulations of the daily CWSI values from plots with different irrigation treatments resulting in different yields (3A) and also for two "replicate" treatments which had different yields (3B). In both cases arrows represent irrigations and the averaging interval is shown.

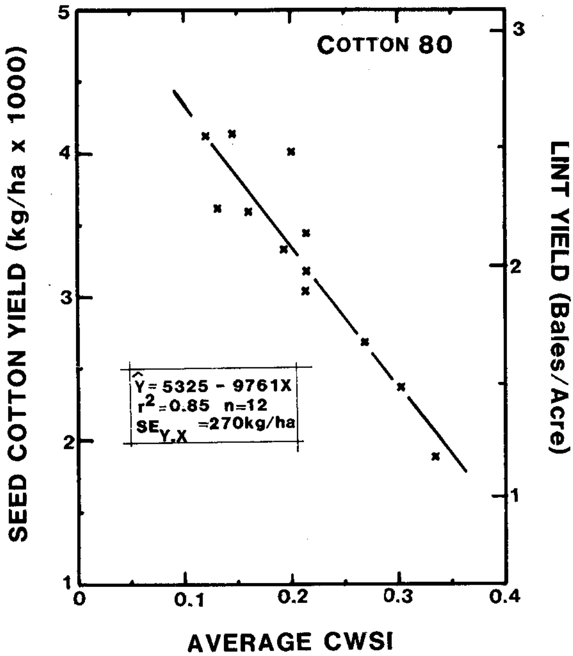


Fig. 4. Cotton yield versus the average daily CWSI measured over the 88-day period from first square until 2 weeks following the last irrigation in August.

time when the yield-producing potential of cotton was considered to be relatively high. The interval began on 31 May, the approximate date when squares (cotton flower buds) greater than approximately 0.3 cm were first observed in the field, and continued until 27 August, 14 days following the last irrigation. Then the CWSI was averaged over this time period. The data are listed in Table I and graphed versus cotton yield in Fig. 4. Analysis by simple linear regression techniques shows that the average CWSI explains most of the variability in cotton yield:

$$\begin{aligned} Y' &= 5325 - 9761\,X \\ R &= 0.92 \quad S_{y \cdot x} = 270 \text{ kg/ha} \end{aligned} \tag{2}$$

where X is the average CWSI and Y' is the seed cotton yield (kg/ha).

The results depicted in Fig. 4 imply that permitting the average CWSI value to exceed 0.20 will probably result in decreased yields. The magnitude of the final yield in a non-determinant crop such as cotton will also be strongly dependent upon the length of the irrigated period. In our experiment, for example, the cotton was terminated relatively early in the season by withholding water after mid-August. If an additional irrigation had been applied, an increase in the final yield might have occurred for the same average CWSI. Thus, additional research is required to define the impact which the total length of the growing season has on the CWSI vs. yield relationships. Because of these considerations, we feel that Fig. 4 might best be viewed as a relative measure of yield. Any deviation from the optimum average CWSI would tend to operate on the potential lint yield established by length of growing season, nutrient supplies and pest interactions.

CONCLUSIONS

We have shown how plant temperatures measured with an infrared thermometer can be combined with ambient air temperatures and vapor pressure deficits to yield a crop water stress index (CWSI) that is a relative measure of the plant's ability to meet evaporative demand. The CWSI offers several important advantages over conventional approaches for quantifying plant stress between irrigations and monitoring yield potential. It is a rapid, non-destructive technique which can be used to survey large acreages in a relatively short period of time.

Practical application of these results to irrigation scheduling in cotton will require further testing. We believe that monitoring the CWSI on a daily basis offers a method whereby irrigations can be timed more appropriately. This is becoming increasingly more important in arid and semi-arid cropping zones where soaring water application costs mean that maximum profits are not always associated with the highest yields and the elimination of any unnecessary irrigation would make cotton growing a more profitable venture. Finally, the timing of irrigation in cotton must be tempered with the requirement to stress the plants appropriately to effect the proper balance between vegetative and reproductive growth patterns. In this case, the CWSI can be used to quantify the extent of stress encountered prior to an irrigation, delaying it if necessary to encourage fruit development.

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